Effective File-I/O Bandwidth Benchmark

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Abstract. The effective I/O bandwidth benchmark (b_eff_io) covers two goals: (1) to achieve a characteristic average number for the I/O bandwidth achievable with parallel MPI-I/O applications, and (2) to get detailed information about several access patterns and buffer lengths. The benchmark examines "first write", "rewrite" and "read" access, strided (individual and shared pointers) and segmented collective patterns on one file per application and non-collective access to one file per process. The number of parallel accessing processes is also varied and wellformed I/O is compared with non-wellformed. On systems, meeting the rule that the total memory can be written to disk in 10 minutes, the benchmark should not need more than 15 minutes for a first pass of all patterns. The benchmark is designed analogously to the effective bandwidth benchmark for message passing (b_eff) that characterizes the message passing capabilities of a system in a few minutes. First results of the b_eff_io benchmark are given for IBM SP, Cray T3E and NEC SX-5 systems and compared with existing benchmarks based on parallel Posix-I/O.

Keywords. MPI, File-I/O, Disk-I/O, Benchmark, Bandwidth.

1 Introduction

Most parallel I/O benchmarks and benchmarking studies characterize the hardware and file system performance limits [2, 4–6]. Often, they focus on determining under which conditions the maximal file system performance can be reached on a specific platform. Such results can guide the user in choosing an optimal access pattern for a given machine and file system, but do not generally consider the needs of the application over the needs of the file system.

Our approach begins with consideration of the possible I/O requests of parallel applications. To formulate such I/O requests, the MPI Forum has standardized the MPI-I/O interface [7]. Major goals of this standardization are to express the user's needs and to allow optimal implementations of the MPI-I/O interface on all platforms [3, 8, 11, 12]. Based on this background, the effective I/O bandwidth benchmark (b_eff_io) should measure different access patterns, report these detailed results, and should calculate an average I/O bandwidth value that characterizes the whole system. This goal is analogous to the Linpack value reported in TOP500 [16] that characterizes the computational speed of a system, and also to the effective bandwidth benchmark (b_eff), that characterizes the communication network of a distributed system [9, 14, 15].

A major difference between b_eff and b_eff_io is the magnitude of the bandwidth. On well-balanced systems in high performance computing we expect an I/O bandwidth which allows for writing or reading the total memory in approximately 10 **minutes**. For the communication bandwidth, the b_eff benchmark shows, that the total memory can be communicated in 3.2 **seconds** on a Cray T3E with 512 processors and in 13.6 seconds on a 24 processor Hitachi SR 8000. An I/O benchmark measures the bandwidth of data transfers between memory and disk. Such measurements are (1) highly influenced by buffering mechanisms of the underlying I/O middleware and filesystem details, and (2) high I/O bandwidth on disk requires, especially on striped filesystems, that a large amount of data must be transferred between such buffers and disk. Therefore a benchmark must ensure that a sufficient amount of data is transfered between disk and the application's memory. The communication benchmark b_eff can give detailed answers in about 2 minutes. Later we shall see that b_eff_io, our I/O counterpart, needs at least 15 minutes to get a first answer.

2 Multidimensional Benchmarking Space

Often, benchmark calculations sample only a small subspace of a multidimensional parameter space. One extreme example is to measure only one point, e.g., a communication bandwidth between two processors using a ping-pong communication pattern with 8 Mbyte messages, repeated 100 times. For I/O benchmarking, a huge number of parameters exist. We divide the parameters into 6 general categories. At the end of each category in the following list, a first hint about handling these aspects in b_eff_io is noted. The detailed definition of b_eff_io is given in section 4.

1. Application parameters are (a) the size of contiguous chunks in the memory, (b) the size of contiguous chunks on disk, which may be different in the case of scatter/gather access patterns, (c) the number of such contiguous chunks that are accessed with each call to a read or write routine, (d) the file size, (e) the distribution scheme, e.g., segmented or long strides, short strides, random or regular, or separate files for each node, and (f) whether or not the chunk size and alignment are wellformed, e.g., a power of two or a multiple of the striping unit. For b_eff_io, 36 different patterns are used to cover most of these aspects.
2. Usage aspects are (a) how many processes are used and (b) how many parallel processors and threads are used for each process. To keep these aspects outside of the benchmark, b_eff_io is defined as a maximum over these aspects and one must report the usage parameters used to achieve this maximum.

3. The major programming interface parameter is specification of which I/O interface is used: Posix I/O buffered or raw, special filesystem I/O of the vendor's filesystem, or MPI-I/O. In this benchmark, we use only MPI-I/O, because it should be a portable interface of an optimal implementation on top of Posix I/O or the special filesystem I/O.
4. MPI-I/O defines the following orthogonal aspects: (a) access methods, i.e., first writing of a file, rewriting or reading, (b) positioning method, i.e., explicit offsets, individual or shared file pointers, (c) coordination, i.e., accessing the file collectively by (all) processes or noncollectively, (d) synchronism, i.e., blocking or nonblocking. Additional aspects are: (e) whether or not the files are open *unique*, i.e., the file will not be concurrently opened by a different open call, and (f) which consistency is chosen for conflicting accesses, i.e., whether or not atomic mode is set. For b_eff_io there is no overlap of I/O and computation, therefore only blocking calls are used. Because there should not be a significant difference between the efficiency of using explicit offsets or individual file pointers, only the individual and shared file pointers are benchmarked. With regard to (e) and (f), *unique* and *nonatomic* are used.
5. Filesystem parameters are (a) which filesystem is used, (b) how many nodes or processors are used as I/O servers, (c) how much memory is used as bufferspace on each application node, (d) the disk block size, (e) the striping unit size, and (f) the number of parallel striping devices that are used. These aspects are also outside the scope of b_eff_io. The chosen filesystem, its parameters and any usage of non-default parameters must be reported.
6. Additional benchmarking aspects are (a) repetition factors, and (b) how to calculate b_eff_io, based on a subspace of the parameter space defined above using maximum, average, weighted average or logarithmic averages.

To reduce benchmarking time to an acceptable amount, one can normally only measure I/O performance at a few grid points of a 1-5 dimensional subspace. To analyze more than 5 aspects, usually more than one subspace is examined. Often, the common area of these subspaces is chosen as the intersection of the area of best results of the other subspaces. For example in [5], the subspace varying the number of servers is obtained with segmented access patterns, and with well-chosen block sizes and client:server ratios. Defining such optimal subspaces can be highly system-dependent and may therefore not be as appropriate for a b_eff_io designed for a variety of systems. For the design of b_eff_io, it is important to choose the grid points based more on general application needs than on optimal system behavior.

3 Criteria

The benchmark b_eff_io should characterize the I/O capabilities of the system. Should we use, therefore, only access patterns, that promise a maximum bandwidth? No, but there should be a good chance that an optimized implementation

type	l	L	U
0	1 MB	1 MB	0
	M_{PART}	$:=l$	4
	1 MB	2 MB	4
	1 MB	1 MB	4
	32 kB	1 MB	2
	1 kB	1 MB	2
	32 kB +8B	1 MB + 256B	2
	1 kB +8B	1 MB + 8kB	2
	1 MB +8B	1 MB + 8B	2

type	l	L	U
1	1 MB	$:=l$	0
	M_{PART}	$:=l$	4
	1 MB	$:=l$	2
	32 kB	$:=l$	1
	1 kB	$:=l$	1
	32 kB +8B	$:=l$	1
	1 kB +8B	$:=l$	1
	1 MB +8B	$:=l$	2

type	l	L	U
2	1 MB	$:=l$	0
	M_{PART}	$:=l$	2
	1 MB	$:=l$	2
	32 kB	$:=l$	1
	1 kB	$:=l$	1
	32 kB +8B	$:=l$	1
	1 kB +8B	$:=l$	1
	1 MB +8B	$:=l$	2
3/4	see type=2		
			$\sum U = 64$

Table 1. The pattern details used in b_eff_io

of MPI-I/O should be able to achieve a high bandwidth. This means that we should measure patterns that can be recommended to application developers.

An important criterion is that the b_eff_io benchmark should only need about 10 to 15 minutes. For first measurements, it need not run on an empty system as long as concurrently running other applications do not use a significant part of the I/O bandwidth of the system. Normally, the full I/O bandwidth can be reached by using less than the total number of available processors or SMP nodes. In contrast, the communication benchmark b_eff should not require more than 2 minutes, but it must run on the whole system to compute the aggregate communication bandwidth. Based on the rule for well-balanced systems mentioned in the introduction and assuming that MPI-I/O will attain at least 50 percent of the hardware I/O bandwidth, we expect that a 10 minute b_eff_io run can write or read about 16 % of the total memory of the benchmarked system. For this estimate, we divide the total benchmark time into three intervals based on the following access methods: initial write, rewrite, and read. However, a first test on a T3E900-512 shows that based on the pattern-mix, only about the third of this theoretical value is transferred. Finally, as a third important criterion, we want to be able to compare different common access patterns.

4 Definition of the Effective I/O Bandwidth

The effective I/O bandwidth benchmark measures the following aspects:

- a *set of partitions*,
- the access methods *initial write*, *rewrite*, and *read*,
- the *pattern types* (see Fig. 1)
  (0) strided collective access, scattering large chunks in memory to/from disk,
  (1) strided collective access, but one read or write call per disk chunk,
  (2) noncollective access to one file per MPI process, i.e., on separated files,
  (3) same as (2), but the individual files are assembled to one segmented file,
  (4) same as (3), but the access to the segmented file is done with collective routines;
  for each pattern type, an individual file is used.

- the contiguous chunk size is chosen *wellformed*, i.e., as a power of 2, and *non-wellformed* by adding 8 bytes to the wellformed size,
- different chunk sizes, mainly 1 kB, 32 kB, 1 MB, and the maximum of 2 MB and 1/128 of the memory size of a node executing one MPI process.

The total list of patterns is shown in Tab. 1. The column "type" refers to the pattern type. The column "l" defines the contiguous chunks that are written from memory to disk and vice versa. The value M_{PART} is defined as *max(2 MB, memory of one node / 128)*. The column "L" defines the contiguous chunk in the memory. In case of pattern type (0), non-contiguous file views are used. If l is less than L, then in each MPI-I/O read/write call, the L bytes in memory are scattered/gathered to/from the portions of l bytes at the different locations on disk, see the left-most scenario in Fig. 1. In all other cases, the contiguous chunk handled by each call to MPI_Write or MPI_Read is equivalent in memory and on disk. This is denoted by ":=l" in the L column. U is a time unit.

Each pattern is benchmarked by repeating the pattern for a given amount of time. This time is given by the allowed time for a whole partition (e.g., $T = 10$ minutes) multiplied by $U/\sum U/3$, as given in the table. This time-driven approach allows one to limit the total execution time. For the pattern types (3) and (4) a fixed segment size must be computed before starting the pattern of these types. Therefore, the time-driven approach is substituted by a size-driven approach, and the repeating factors are initialized based on the measurements for types (0) to (2).

The b_eff_io value **of one partition** is defined as the sum of all transferred bytes divided by the total transfer time. If patterns do not need exactly the ideal allowed time, then the average is weighted by the unit U. At a minimum, 10 minutes must be used for benchmarking one partition. **The b_eff_io of a system** is defined as the maximum over any b_eff_io of a single partition of the system. This definition permits the user of the benchmark to freely choose the usage aspects and enlarge the total filesize as desired. The minimum filesize is given by the bandwidth for an initial write multiplied by 200 sec (= 10 minutes / 3 access methods). If a system complies with our rule that the total memory can be written in 10 minutes for each access pattern, then one third of the total memory is written by the complete benchmark, and in each single pattern with U=1, one 1/192 of the total memory is written. If all processors are used for this benchmark, then the amount written by each node is not very much, but a call to MPI_File_sync in each pattern may imply that the data is really written to disk. However this assumption is not valid on all systems. For example, on NEC SX systems, MPI_File_sync guarantees only the semantic stated in the MPI-2 standard. The data on the file must be visible to any other application, but the data can stay in a memory buffer controlled by the filesystem's software. Therefore the benchmark rule, that at least 10 minutes are used for one run, had to be modified for this system. In the current version we use for the SX-5 measurements, we require that the total amount of data written with the initial write-calls must be at least equal to the total amount of the memory of the system. Thus, on the SX-5 we had to increase the scheduled benchmark time to T=30 minutes.

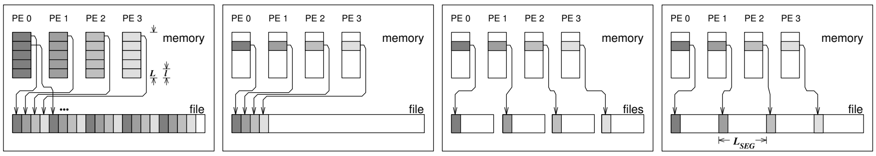
5 Comparing Systems Using b_eff_io

In this section, we present a detailed analysis of each run of b_eff_io on a partition. We test b_eff_io on three systems, the Cray T3E900-512 and SX-5Be/32M2 at HLRS/RUS in Stuttgart and an RS 6000/SP system at LLNL called "blue." On the T3E, we use the tmp-filesystem with 10 striped Raid-disks connected via a GigaRing for the benchmark. The peak-performance of the aggregated parallel bandwidth of this hardware configuration is about 300 MB/s. The LLNL results presented here are for an SP system with 336 SMP nodes each with four 332 MHz processors. Since the I/O performance on this system does not increase significantly with the number of processors on a given node performing I/O, all test results assume a single thread on a given node is doing the I/O. Thus, a 64 processor run means 64 nodes assigned to I/O, and no requested computation by the additional 64*3 processors. On the SP system, the data is written to the IBM General Parallel File System (GPFS) called blue.llnl.gov:/g/g1 which has 20 VSD I/O servers. Recent results for this system show a maximum read performance of approximately 950MB/sec for a 128 node job, and a maximum write performance of 690MB/sec for 64 nodes [5].[1] Note that these are the maximum values observed, and performance degrades when the access pattern and/or the node number is changed. The NEC SX-5 system has four striped RAID-3 arrays DS 1200, connected by fibre channel. The SFS filesystem parameters are: 4 MB cluster size (=block size), and if the size of an I/O request is less than 1 MB then a 2 GB filesystem-cache is used.

On both platforms, MPI-I/O is implemented with ROMIO but with different device drivers. On the T3E, we have modified the MPI Release mpt.1.3.0.2, by substituting the ROMIO/ADIO Unix filesystem driver routines for opening, writing and reading files. The Posix routines were substituted by the asynchronous counter part, directly followed by the the wait routine. This trick enables parallel disk access [13]. On the RS 6000/SP blue machine, GPFS is used underneath the MPICH version of MPI with ROMIO. On the SX-5, we use MPI/SX 10.1.

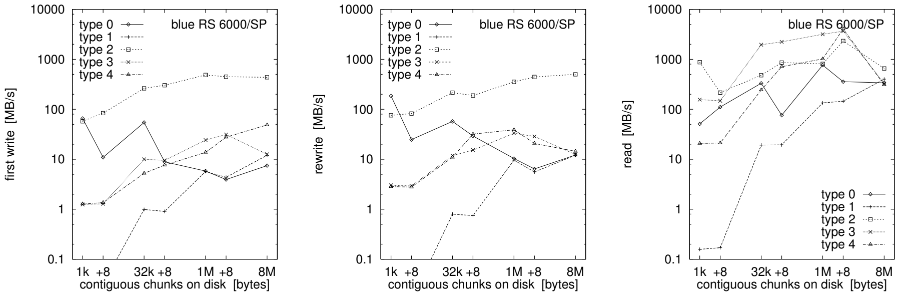
For each run of b_eff_io, the I/O bandwidth for each chunk size and pattern is reported in a table that can be plotted in the pictures shown in each row in Fig. 2. First, consider the first two rows of Fig. 2. They show the results of one benchmark on the SP and T3E systems, both scheduled to run $T = 10$ minutes, during which time other applications were running on the other processors of the systems. They demonstrate the main differences between both MPI and filesystem implementations. Based on the results in Fig. 3, which we discuss later, we decided to run the benchmark on the T3E on 32 processors and on the SP

[1] Upgrades to the AIX operating system and underlying GPFS software may have altered these performance numbers slightly between measurements in [5] and in the current work.

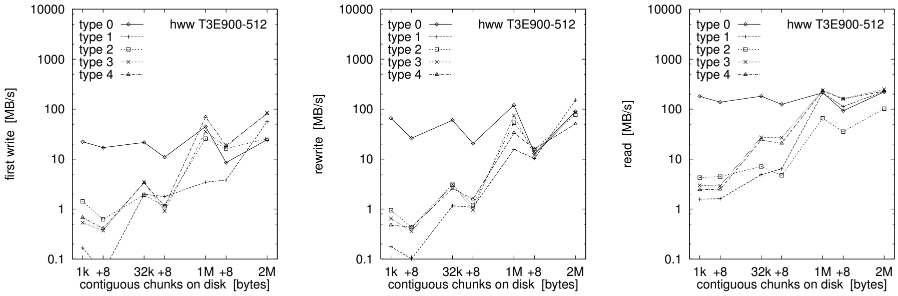


pattern type 0 pattern type 1 pattern type 2 pattern type 3/4

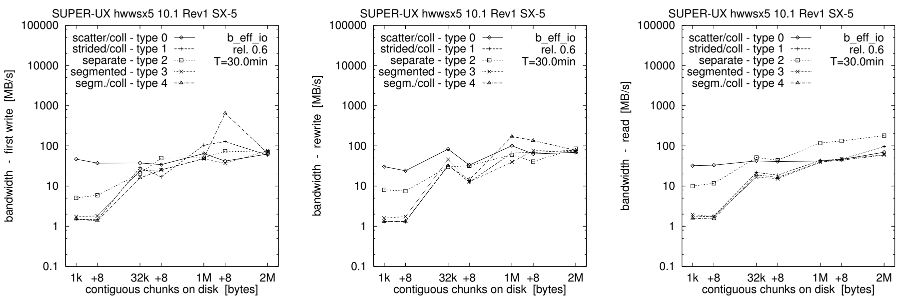
Fig. 1. Data transfer patterns used in b_eff_io. Each diagram shows the data transferred by **one** MPI-I/O write call.



(a) 128 PEs on the "blue" RS 6000/SP at LLNL, $T = 10$ min, b_eff_io = 311 MB/s



(b) 32 PEs on the T3E900-512 at HLRS, $T = 10$ min, b_eff_io = 71 MB/s



(c) 4 PEs on the SX-5Be/32M2 at HLRS, $T = 30$ min, b_eff_io = 60 MB/s

Fig. 2. Comparison of the results on T3E, SP and SX-5

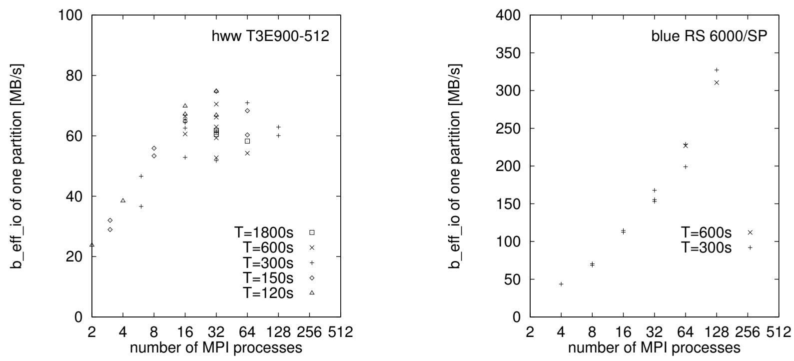


Fig. 3. Comparison b_eff_io of different numbers of processes on SP and T3E, measured partially without pattern type 3.

on 128 processors. The three diagrams in each row of Fig. 2 show the bandwidth achieved for the three different access methods: writing the file the first time, rewriting the same file, and reading it. On each diagram, the bandwidth is plotted on a logarithmic scale, separately for each pattern type and as a function of the chunk size. The chunk size on disk is shown on a pseudo-logarithmic scale. The points labeled "+8" are the non-wellformed counterparts of the power of two values. The maximum chunk size is different on both systems because the maximum chunk size was chosen proportional to the memory size per node to reflect the scaling up of applications on larger systems. On the SX-5, a reduced maximum chunk size was used.

Type 0 is a strided access, but the buffer used in each I/O-call is at least 1 MB. In the case of a chunk length less than 1 MB, the buffer contents must be scattered to different places in the file. On the T3E, this pattern type is optimal, except for chunks larger than 1 MB, where the initial write of segmented files is faster. When non-wellformed chunk sizes are used, there is a substantial drop in performance. Additional measurements show that this problem increases with the total amount of data written to disk. On the RS 6000/SP, other pattern types show higher bandwidth.

Type 1 writes the same data to disk, i.e., each process has the same logical fileview, but MPI-IO is called for each chunk separately. In the current benchmark, this test is done with individual filepointers, because the MPI-I/O ROMIO implementation on both systems does not have shared filepointers. By default, b_eff_io measures this pattern type with shared pointers when available. On both platforms, this pattern type results in essentially the worst bandwidth for most access methods and chunk sizes.

Type 2 is the writing winner on RS 6000/SP. Each process writes a separate file at the same time, i.e., parallel and independently. (We note that optimized vendor supplied MPI-IO implementations may do a better job with other pattern types.) Type 3 writes in the same pattern, but the files of all processes are concatenated. To guarantee wellformed starting points for each process, the filesize of each process is rounded up to the next MByte. Type 4 writes in the same way as type 3, but the access is done collectively. On the T3E, we see that these three pattern types are consistently slow for small buffer sizes and consistently fast for large buffer sizes. In contrast on the RS 6000/SP, type 3 and 4 are about a factor[2] of **10–20** slower than type 2 for writing files. For reading files, the diagram cannot show the real speed for type 3 and 4 due to three effects: The repetition factor is only one for chunk sizes of 1 MB and more, the reading of the 8 MB chunk fills internal buffers, and currently, the b_eff_io does not perform a file sync operation before reading a pattern. Looking at the (non-weighted) average, we see that on the RS 6000/SP, reading the segmented files is a factor of **2.5** slower than reading individual files.

Finally on both systems, the read access is clearly faster than the write access. On the T3E, the read access is 5 times faster than "first write" and 2.7 faster than "rewrite". On the RS 6000/SP blue machine, the read access is 10 times faster than both types of write access. The measurements were done with b_eff_io Release 0.5 [10].

The last row of Fig. 2 shows the measurement on the SX-5. It had to be done with the longer schedule time of T = 30 minutes to assure that most of the I/O operations are done on real disks and not only in the filesystem's internal buffer space. The curves show still some hot spots that may be caused by pure memory copying. One can see that the scattering-pattern type 0 and the separate-file-pattern type 2 perform the best. There is little difference between wellformed and non-wellformed I/O. Write and read bandwidth are similar. For long chunk sizes, reading from separate files (pattern type 2) is faster than the gathering/strided accesses (type 0 and 1) and the segmented accesses (type 3 and 4).

Figure 3 shows the b_eff_io values for different partition sizes and different values of T, the time scheduled for benchmarking one partition. All measurements were taken in a non-dedicated mode. For the T3E, the maximum is reached at 32 application processes, with little variation from 8 to 128 processors. In general, an application only makes I/O requests for a small fraction of the compute time. On large systems, such as those at the High-Performance Computing Center at Stuttgart and the Computing Center at Lawrence Livermore National Laboratory, several applications are sharing the nodes, especially during prime time usage. In this situation, I/O capabilities would not be requested by a significant proportion of the CPU's at the same time. "Hero" runs, where one application ties up the entire machine for a single calculation are rarer and generally run during non-prime time. Such hero runs can require the full I/O performance by all processors at the same time. The right-most diagram shows that the RS 6000/SP fits more to this latter usage model. Note that GPFS on the SP's is configurable, i.e., number of I/O servers and other tunables, and the performance on any given SP/GPFS system depends on the configuration of that system.

[2] All factors in this section are computed, based on weighted averages using the time units U, if not stated otherwise.

Figure 3 also shows that on both systems, the results depend more on the I/O usage of the other concurrently running applications on the system than on the requested time T for each benchmark. Comparison of measurements with $T = 10$ and 30 minutes shows that the analysis reported in Fig. 2 may vary in details. For instance, the differences between wellformed and non-wellformed I/O is more notable with $T = 30$ minutes on the T3E.

Finally, we compare these results with other measurements. On the same RS 6000/SP, Posix read and write measurements ranging between 500 and 900 MB/s are measured [5]. [3] The b_eff_io result is 311 MB/s in the presented measurement. This means that the MPI application programmer has a real chance to get a significant part of the I/O capabilities of that system. On the T3E studied, the peak I/O-performance is about 300 MB/s. Thus the b_eff_io value of 71 MB/s shows that on average, only a quarter of the peak can be attained with normal MPI programming. We also note that the ROMIO implementation on the RS 6000/SP has not been optimized for the GPFS filesystem. Vendor implementations and future versions of ROMIO should show performance closer to peak.

In general, our results show that the b_eff_io benchmark is a very fast method to analyze the parallel I/O capabilities available for applications using the standardized MPI-I/O programming interface. The resulting b_eff_io value summarizes I/O capabilities of a system in one significant I/O bandwidth value.

6 Outlook

It is planned to use this benchmark to compare several additional systems. More investigation is necessary to solve problems arising from 32 bit integer limits and handling read buffers in combination with file sync operations. Although [1] stated, that "the majority of the request patterns are sequential", we should examine whether random access patterns can be included into the b_eff_io benchmark.

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[3] Again we note that upgrades to the AIX operating system and underlying GPFS software may have slightly altered these performance numbers between measurements.

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